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THESIS

OPTIMIZATION OF MARINE FORCES RESERVE EQUIPMENT REDISTRIBUTION

by

Nicolas L. Martinez

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Thesis Advisor:	Javier Salmerón
Second Reader:	Robert M. McGuiness

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13. ABSTRACT (maximum 200 words)

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OPTIMIZATION OF MARINE FORCES RESERVE EQUIPMENT REDISTRIBUTION

Nicolas L. Martinez
Major, United States Marine Corps
B.S., United States Naval Academy, 2005
M.S., University of San Diego, 2011

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June 2016

Approved by: Javier Salmerón
Thesis Advisor

Robert M. McGuiness
Second Reader

Patricia A. Jacobs
Chair, Department of Operations Research

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ABSTRACT

This research creates the Marine Corps Equipment Redistribution Model (MCERM). MCERM is a mathematical optimization model that can be used as a decision-support prototype to guide Marine Forces Reserve (MARFORRES) in planning asset redistribution to satisfy subordinate units' training and equipping requirements. MCERM implements a mixed-integer, linear program that selects sets of equipment transfers between units in order to raise overall readiness for priority units. MCERM optimally minimizes both (a) a function of transit distance and equipment size to transfer equipment to a unit (used as a surrogate for actual transfer cost), and (b) inventory shortages. MCERM allows planners to influence recommended transfers by (a) placing a weighted penalty on transfers that cross between commands, and (b) increasing the shortage penalty over the transfer penalty. It also enables the use of substitute equipment at an additional penalty. A realistic test case analyzes all equipment to unit ownerships reported by MARFORRES on April 22, 2016. From the results, MCERM's recommended transfers decreased the overall shortage penalty by a large margin while incurring a relatively low transfer penalty. This prototype enables planners to review the entire MARFORRES equipment redistribution problem, select optimized solutions, and perform fast sensitivity analysis on the competing objectives.

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LIST OF ACRONYMS AND ABBREVIATIONS

BRAC	Base Realignment and Closure
DIV	Marine Division
DMO	Distribution Management Office
FHG	Force Headquarters Group
GCSS-MC	Global Combat Support Systems-Marine Corps
IM/KM	Information Management / Knowledge Management
LOGCOM	Logistics Command
MARES	Marine Corps Automated Readiness Evaluation System
MARFORRES	Marine Forces Reserve
MAW	Marine Air Wing
MCERM	Marine Corps Equipment Redistribution Model
MEE	Mission Essential Equipment
H&S	Headquarters and Services Battalion
MLG	Marine Logistics Group
MPORAM	Multi-Period Optimal Readiness Allocation Model
MSC	Major Subordinate Command
ORAM	Optimal Readiness Allocation Model
RTC	Reserve Training Center
SP-MAGTF	Special-Purpose Marine Air-Ground Task Force
TA	Training Allowance
UIC	Unit Identification Code

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EXECUTIVE SUMMARY

Marine Forces Reserve (MARFORRES) units operate in more than 150 various locations across the United States. Due to the large number of geographically dispersed reserve units and associated logistical challenges, not all reserve units physically possess their full set of requisite gear needed with which to train in order to maintain proficiency or meet pre-deployment requirements. This supply deficit requires that equipment be transferred among MARFORRES units in order to ensure operational support and training requirements are met. Therefore, equipment redistribution between reserve units is a continuous operation coordinated by MARFORRES G-4 Supply.

Redistribution is currently planned on a monthly basis by a staff working group relying on individual experience with the training schedules and knowledge of past redistributions. Short-term objectives can lead to cross-leveling equipment between units with the shortest distance. However, it is difficult for individual planners to find redistributions that strike a proper balance among the multiple competing goals. MARFORRES G-4 and the Information Management / Knowledge Management office have requested advanced decision support methods, based on formal mathematical modeling, to prescribe optimal monthly equipment redistribution in order to increase unit readiness and support operational and training requirements. This thesis research fulfills that need through the development of the Marine Corps Equipment Redistribution Model (MCERM).

MCERM is a mixed-integer, linear program designed to recommend a series of equipment transfers (redistribution) among MARFORRES units to decrease equipment shortages experienced by those units while minimizing the transfer cost. Specifically, MCERM recommends optimal transfers that minimize the sum of three competing terms: the distance-size penalty function for transfers, the penalty for substitutions, and the penalty for shortage between what units require and own.

We utilize a small-case test and a full-case test to challenge the MCERM. The small-case test mirrors the full-case test information but with only 187 equipment-to-unit

pairings. This case allows for extensive testing and validation of functionalities. The full-case test includes all equipment and unit ownership as reported by MARFORRES on April 22, 2016. The test comprises over 400 units (as categorized by unit identification codes), 1,500 equipment types and 42,000 equipment-to-unit pairings with 1.2 million individual equipment items. Both cases are analyzed for transfer penalty, inventory shortages and associated penalty, quantities transferred, and employment of substitutes.

MCERM calculates solutions based on input data and planner-applied weights. Input files are comma-separated files derived from web-based reports of current on-hand equipment levels by unit along with amplifying information on location, size, and priority of units and equipment. Planners implement preferences to MCERM solutions by enabling control on the relative importance of the competing terms: First, the user can increase or decrease the overall shortage penalty, thereby concentrating minimization on either the transfer penalties or the shortage penalties. Second, the planner can add a penalty for transfers that travel between major subordinate commands in order to discourage, to a desired degree, these types of transfers.

In the full-case test, MCERM raises the number of units with 80% of their total equipment requirement from 20 to 148, which reduces the number of units with less than 60% of their equipment from 321 to 157. This overall increase significantly improves overall operational readiness for MARFORRES and does so at a relatively low transfer penalty. Further decreasing the inventory shortages incurs much larger transfer costs. By performing sensitivity analysis on the importance of the different goals, an efficient-frontier curve of “transfer penalty vs. shortage penalty” can be generated. This can be used by decision makers to leverage a course of action which minimizes shortages at acceptable cost levels. Based on the results of this study, it is recommended that MARFORRES G-4 implements MCERM as a decision-support prototype in order to improve current redistribution planning and practices.

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I. INTRODUCTION

This thesis develops the Marine Corps Equipment Redistribution Model (MCERM). MCERM is an optimization model implemented as a decision-support prototype to assist Marine Forces Reserve's (MARFORRES) monthly, or as required, equipment redistribution among units. MCERM recommends optimal equipment transfers that minimize a function of travel distance between units and inventory shortages to meet operational and training objectives.

A. BACKGROUND

Military reserves provide skill-level depth and manpower to the armed forces of the United States of America. The reserves live and work full time in the civilian sector, volunteering to serve part-time in the military auxiliary forces which can be activated in times of need. Reservists from all branches of the military deploy on a rotational basis and have fought in the recent wars of Iraq and Afghanistan. MARFORRES, comprised of both active duty and reserve Marines, exists to augment and reinforce active component forces at home and aboard.

Operating in more than 150 locations across the United States, MARFORRES comprises from four major subordinate commands (MSCs): 4th Marine Division (DIV), 4th Marine Air Wing (MAW), 4th Marine Logistics Group (MLG), and Force Headquarters Group (FHG). Marine reserve units reside on Reserve Training Centers (RTCs) and are not normally co-located with their parent, subordinate or adjacent units. These RTCs range in facility size, personnel manning, budgets, training objectives, proximity to their respective MSC, and mission assignment, with no unifying locational directive. In other words, approximately 400 reserve units (as categorized by unit identification codes (UIC)) are spread out across the United States in various sizes and capability sets. Each RTC possesses a unique set of limitations on how much equipment can be maintained and stored on site. Due to the large number of geographically dispersed RTCs and associated logistical challenges (inventory adjustments, obsolete equipment, maintenance, etc.), not all reserve units are capable of maintaining their full inventory of authorized equipment. Consequently, items need to be transferred among units.

Units must meet training objectives within specific readiness timelines, and many of the training events require certain types and quantities of equipment. For example, a reserve infantry battalion's pre-deployment training cycle takes five years for the unit to be operationally prepared for mobilization and deployment. This training cycle often involves a corresponding transfer of equipment within the force to meet timeline requirements. Thus, equipment reallocation among reserve units is a continuous operation coordinated by the MARFORRES G-4 Supply section on a monthly basis. Approximately 1.2 million individual items across over 1,500 types of equipment are in use by MARFORRES and subject to transfer.

The G-4 Supply section relies on individual experience with the training schedules, current supply reports, and knowledge of past redistributions to accomplish this task. The working group's short term objectives lead to cross-leveling equipment among units with relative proximity in order to minimize shipping costs. The group encounters limitations in reviewing locations of all 400 MARFORRES units with equipment levels and identifying potential cross-leveling of equipment to support the multi-year training cycle. The resulting cost for the overall monthly redistribution is not optimized over a broader period or across all the units.

MARFORRES G-4 and the Information Management / Knowledge Management (IM/KM) office request advanced decision support methods, based on formal mathematical modeling, to prescribe optimal monthly equipment redistribution in order to increase unit readiness and support operational and training requirements. This research follows and supports the MARFORRES G-4 and IM/KM request.

B. SPECIFICATIONS OVERVIEW

MCERM should be based on mathematical optimization and operate within the physical constraints from which the Marine Corps works. The resulting transfers selected by the model should strike a balance between redistribution travel distance and equipment shortage levels across all MARFORRES units. Inventory shortage is measured (for each unit and equipment type) with respect to the table of allowance (TA) as determined by the unit's Commanding Officer.

In addition, MCERM should also factor a unit's training cycle priority. At any given time, units are at different stages of their training cycle and therefore have a different urgency to be supplied. While some units may offer proximity advantage for a transfer, the priority will be preferentially weighted. MCERM needs to review the entire force and all candidate equipment for this redistribution.

MARFORRES possesses specific requirements according its own procedures regarding equipment status, substitutions, and command integrity. Equipment exists in either an archived, disposal, or in-service status. Due to challenges of a geographically dispersed force, many MARFORRES units possess older equipment items despite being outdated and slated for disposal. MARFORRES current policy seeks to only transfer equipment with an in-service status between units. This restriction ensures older equipment can be monitored and maintained by a consistent unit prior to its disposal.

A further requirement is that MCERM accounts for the possibility of utilizing equipment substitutes in place of required equipment. The Marine Corps designates different equipment types which perform similar functions as substitutes of each other. For example, a unit may require a radio with a certain strength and design. If that radio is in high demand or limited in quantity, a different older radio model can substitute for it even if it is a less preferred option. The opposite occurs as well where an older model radio is substituted by the newer model. MARFORRES frequently directs the use of substitutes in order to avoid purchasing a new equipment item or shipping from units far away. MCERM should balance the use of a substitute with the distance and shortfall objectives.

Finally, MARFORRES strives to support individual commanders to avoid issues associated with transfers crossing between MSCs. This encourages equipment transfers where MSC commanders can engage in the process to ensure success of their units. The only exception to the MSC list is the inclusion of the MARFORRES Headquarters and

Services Battalion (H&S) based on G-4 Supply guidance. Therefore, MCERM should optimize transfers to keep equipment within the same MSC where possible.

C. THESIS OBJECTIVES AND SCOPE

This work develops and computationally implements MCERM, a mathematical optimization model to recommend sourcing and fielding of equipment adhering to specifications outlined in Section B. It utilizes data reflecting unit and equipment characteristics such as type and TA requirement, location and distance, MSC, etc.

The immediate goal of this endeavor is to initiate baseline work on a formal mathematical optimization decision support tool that (a) can help planners assess monthly equipment redistribution decisions, and (b) can serve as the template for future work. As research evolves, it is anticipated that a fully integrated decision support tool will be created, maintained and improved incrementally from the prototype. Ultimately, MCERM is envisioned as an operational planning tool for designing equipment cross-leveling schedules guided by a formal mathematical optimization model.

Further, this tool can be potentially used to direct MARFORRES acquisition focus and support continued analysis of the supply network. Its results will require review by planning staff, but we anticipate MCERM will eliminate hours of work and suggest solutions that would otherwise be complicated to identify by planners.

The analysis in this thesis is made for the months of February through April 2016 across all units and equipment in MARFORRES, as reported by the G-4 Supply section. Specifically, these data have been provided to the author based on a Global Combat Support Systems-Marine Corps (GCSS-MC) report [1]. Qualifying substitutions and unit locations derive from information provided by MARFORRES in April 2016 [2].

II. LITERATURE REVIEW

Two past studies analyze similar facets of asset redistribution in a network and serve as relevant sources for this work, along with the generalized, combined studies and reviews of base realignment. Persons creates an optimization tool to reallocate military equipment among U.S. Army units to increase overall supply readiness [3], [4]. Bertrand and Bookbinder also study reallocation optimization across retail stores in the private sector. In their article, the authors compare benefits of lateral supply shipments between retailers with a central warehouse to a supply network without lateral shipments [5]. Two studies into the process of military base consolidation, known as Base Realignment and Closure (BRAC) [6], [7] are mentioned in this review for their academic contribution to the collective knowledge and understanding of locations, manpower, units, and equipment optimization within the military.

A. THE UNITED STATES ARMY'S MULTI-PERIOD OPTIMAL READINESS ALLOCATION MODEL

The United States Army's Multi-Period Optimal Readiness Allocation Model (MPORAM) is an equipment redistribution decision support tool. It identifies the optimal reallocation of Army equipment that can raise the overall readiness of the force at large [3]. All Army units possess varying quantities of equipment which contribute to determine an S-rating. The S-rating derives from a unit's percentage inventory of all equipment types required with the exception of mission critical equipment types, known as pacing items. Pacing items define the unit's ability to complete essential operational requirements. Because of these considerations, a unit never earns an S-rating better than any single pacing item (e.g., a unit's equipment is stocked at a rating of S-1 except for tanks, which is an essential item and filled at an S-2 rating; therefore, the entire unit is rated at S-2). The Army commissioned a Naval Postgraduate School faculty and student team to develop a model that will raise the entire force's S-rating through a series of item transfers between units. The team developed the Optimal Readiness Allocation Model (ORAM), which reviews a single period and directs redistributions [4]. Persons reviews this ORAM formulation and applies it over multiple time periods adjusting for changing priorities and equipment levels, creating MPORAM. The MPORAM reviews the same equipment distribution and seeks to raise S-ratings over multiple periods with changing priorities. He concludes that the MPORAM demonstrates no large or notable advantage when compared to ORAM. Persons expects that the gap between supply and demand should decrease for the “MPORAM to improve on the single-period solution in more balanced cases” [3].

Both ORAM and MPORAM studies provide a detailed review on considerations and mathematical controls in building an optimization redistribution model comparable to MCERM. First, the models work with prioritization of units. Army units that are closer to deployment receive a higher priority to have their equipment quota filled compared with units which recently returned from a deployment. This is a similar process for MARFORRES with the exception that some units will remain in constant state of their highest priority. Second, ORAM and MPORAM optimize the S-ratings through re-distribution [3], [4]. In other words, a unit needing 90 equipment items with 80 on-hand will rank at an S-2 for that equipment; but, if just one item is transferred to the unit to make 81 now on-hand, that equipment for the unit is rated S-1. MARFORRES does not possess enough available equipment in inventory for using the S-ratings system to measure supply fill. Instead, MARFORRES uses an adjusted scale for equipping units with the TA. MCERM minimizes the equipment shortage using a piecewise linear penalty, which is correlated to the S-rating but does not follow the same rules. Lastly, ORAM and MPORAM do not optimize distance between units for equipment transfers, whereas MCERM minimizes a function of distance and equipment size. This difference sets the MCERM study apart as a readiness allocation model with competing goals related to both distance and shortage.

Person’s conclusion that multiple single periods optimized sequentially display no large disadvantage over a full multi-period optimization helps this thesis. MCERM also reviews a single redistribution period at a time. After MCERM has been in use and the gap between supply and MARFORRES demand decreases, MCERM could be considered for a multi-period review. The MPORAM study is also useful for future developments of

MCERM as more equipment becomes available and the MARFORRES seeks to manage unit equipment by S-ratings.

B. STOCK REDISTRIBUTION IN TWO-ECHELON LOGISTICS SYSTEMS

L.P. Bertrand and J.H. Bookbinder's article focuses on a two-echelon logistics system that is similar to the military supply system studied in this thesis. They study the cost savings and benefits to a logistics network by allowing lateral supplying between retailers rather than paying for expedited supply from the warehouse [5]. While the article does not mention a specific business type or company, the authors promote the study as applicable to many retail-type companies. In other words, their study's relevance is the same whether the retailer is selling clothes or books. For argument's sake, we choose the clothing industry as an example. Bertrand and Bookbinder begin with a basic supply chain logistics model of a large warehouse supplying a number of retail stores (more than two with different distances or associated travel costs) with a variety of apparel for sale. As demand increases on certain retail stores for specific clothing items as opposed to others, the warehouse must now expedite shipments of those shirts or pants to said locations at increased penalty to keep the store in-stock before the next scheduled shipment. In this situation, the authors add a second echelon by enabling the stores to shift merchandise to another store in need and optimize this store-to-store exchange due to different shipment costs [5]. This horizontal re-supply method eliminates the expedited cost to keep a store in stock and creates a more efficient inventory management system. Further, the model penalizes these lateral shipments with associated transfer costs. The second echelon shipments become redistributions of the apparel merchandise in order to meet demand.

In the context of Bertrand and Bookbinder's study, MCERM will be an optimization model for echelon lateral movements between units rather than regular supply shipments from headquarters. As in the two-echelon model, units have various applied prioritization among their peers. However, the purchase of new equipment is not an option for MCERM while Bertrand and Bookbinder's model weighs the cost and expediency of warehouse shipment versus lateral supplying. MCERM will have the ability to accept supply injects of items, as though from a warehouse in this private sector example. For the sake of this thesis, Marine Logistics Command (LOGCOM), a separate Marine command from MARFORRES, can be viewed as MARFORRES' warehouse. LOGCOM operates two Marine Corps equipment depots which purchase and refurbish equipment for the entire Marine Corps. LOGCOM will notify MARFORRES of available equipment and request the G-4 section to direct desired shipments. However, these equipment availabilities are on a non-interval basis and with various equipment types and quantities. Because of the unpredictable nature of these supply injects and LOGCOM's responsibility for the transfer, MCERM factors LOGCOM as just another unit but with a small transfer penalty incurred by MARFORRES.

C. BASE REALIGNMENT AND CLOSURE

Several BRAC studies have developed models to optimize the cost associated with closing bases, realigning units and designing the movement of troops and equipment across the country (see e.g., [6]. and [7]). In a strategic cost-savings initiative, Congress mandates that units be consolidated to selected bases so that other bases may be closed thereby decreasing the overall cost in keeping more bases open than needed. This large scale optimization problem exists as a cyclic event in the country with accompanying studies providing recommendations on how best to support the military force with the right amount and location of bases.

BRAC studies consider, to a lesser extent, equipment movements. They focus mainly on unit demand, capability, and spacing in the active component forces. Recommendations focus on bases to be closed and units to transfer to another base with the objective of minimizing cost and distance. The scope of MCERM focuses exclusively on equipment between units in the reserve force. Future developments of unit movements and requirements may require a more complete implementation of BRAC modeling into MCERM as MARFORRES consolidates units at fewer reserve training centers (see [8]).

III. MCERM METHODOLOGY AND DATA

This chapter describes the assumptions, limitations, data, formulation, and implementation of the model.

A. ASSUMPTIONS

MCERM optimizes a weighted function of cost and distance traveled by equipment. In order for MCERM's recommendations to be valid, the following assumptions must hold:

- Accuracy of the TA: TA is an adjusted command line for the required unit equipment. MARFORRES developed the TA concept as a method to quantify the actual equipment a unit has the capability to store and maintain. The scope of MCERM is not to correct errors but to evaluate the best set of recommended transfers assuming the TA is accurate.

- Accuracy of equipment reported on-hand: Equipment transitions are in a constant state of movement for MARFORRES. While some equipment may be in transition or in the process of being disposed, the model does not determine the validity of whether on-hand equipment numbers are accurate. MCERM accounts for prescribed transfers by the planners to ensure that a unit will not be directed to transfer the same item more than once. This requires accuracy of both on-hand and directed-transfer data.

- Maintenance status of the equipment: Equipment used in support of military operations lives a hard-use lifespan within military units. MCERM assumes all equipment to be fully functional, without maintenance issues, and operational for transfer. This supposition keeps pace with maintenance objectives that non-operational equipment is immediately fixed and places the responsibility on the owning unit to accomplish.

- Size-distance estimation: No codified method or simple calculation has been found to represent the cost to transfer equipment between units. This gap exists because all equipment movements are done through a contracting and bidding process managed by the Distribution Management Office (DMO). This creates difficulty in modeling, for example, a set cost per mile by equipment type. MCERM creates a surrogate cost where bigger items and longer distances are penalized more.

B. LIMITATIONS

MCERM is a representation of equipment redistribution and cannot fully describe or characterize every facet of the reallocation process. MCERM does not accurately model the following features:

- Multi-period problem: MCERM is designed on providing recommendations for a single distribution period (typically a month) corresponding with MARFORRES current practices. MCERM will need to be recalibrated each period with new inputs and re-run by the redistribution working group as often as needed.

- Grouping of equipment: Due to federal laws and the sensitivity of certain equipment, transportation of specific gear types incurs an additional cost because of required supplementary security and safeguarding. These transfers are called bonded shipments. DMO attempts to group these equipment shipments together to reduce cost. In other words, a bonded shipment of a rifle results in the same cost as shipping ten rifles along the same route. Therefore, the grouping of some equipment can be beneficial in saving cost. MCERM neither recommends groupings of shipments from one location to another nor accounts for their potential cost savings.

- Sets of solutions: Alternative courses of action can be generated by re-running MCERM with different priorities and other weights (described later). However, MCERM offers only one optimized set of recommended transfers per run. That is, in each run, MCERM does not provide alternative optimal (or near-optimal) solutions even if such solutions may exist in some cases.

C. DATA SETS

All data inputs into MCERM are comma-separated files drawing on data provided by G-4 Supply through GCSS-MC, G-3 Operations unit guidance, and Marine Corps orders. A description of these files can be found in Table 1. The following characteristics are considered for the input data:

- Units and Equipment: The Marine Corps utilizes the GCSS-MC online equipment tracking method employing bottom-up information collection to track unit maintenance and supply. A generated report from this system by MARFORRES G-4 produces the needed table of information with equipment-to-unit pairings by quantity. In other words, the primary data input is unit’s current TA, on-hand with in-service status, and on-hand total per equipment type.

Table 1. MCERM Inputs.

File	Description
C.csv	List of MSCs in the MARFORRES: DIV, MAW, MLG, FHG, and H&S.
E.csv	List of equipment types currently in use by MARFORRES.
E_data.csv	Table of equipment attributes: size (ft^3); minimum requirement scaling (for the test cases we use 5, 10 or 15 with higher value meaning increased necessity and measure of importance to a unit); and substitution penalty.
EU.csv	GCSS-MC derived table listing unit and equipment type pairs with quantities of TA; on-hand with in-service status; and total on-hand equipment.
F.csv	Substitutions list of equipment: equipment B can substitute for a unit's equipment A requirement.
misc.csv	Miscellaneous data. Planner assigns the *cFactor* and weight *w*.
mover_x.csv	List of transfers already directed by MARFORRES. Listed as equipment type; unit from; unit to; and quantity.
movers_xf.csv	List of transfers which are substitutions already directed by MARFORRES. Listed as equipment type; substitute equipment type; unit from; unit to; and quantity.
priority.csv	List of units with corresponding priority number (range 1 to 6).
U.csv	List of units by their UIC.
UC.csv	Units with their corresponding MSC.
Uzip.csv	Units with their corresponding zip code.
zip	List of all zip codes with MARFORRES units.
zip_dist.csv	List of distances from each zip code to another in miles.

- Equipment size and importance: Each equipment size is recorded in cubic feet. Equipment is also divided into three groups of importance to Marine core mission sets listed from most critical to least: Mission Essential Equipment (MEE), Marine Corps Automated Readiness Evaluation

System (MARES), and Non-MARES. These categories are associated with weights corresponding to relative importance that, for our testing purposes, we set as follows: 15 for MEE, 10 for MARES, and 5 for Non-MARES. These numbers contribute to developing the shortage penalty so a deficiency in MEE items would have a larger penalty than in Non-MARES.

- Unit locations and priority: The units are located by zip codes. Therefore, more than one unit can be located in the same zip code; in such a case the distance is recorded evenly as 0.5 miles. G-3 Operations assigns each unit a numeric priority weight with the higher number indicating highest priority. For testing purposes, we set priority values ranging from 1 to 6.

- Substitutions and associated penalty: A substitute is a similar type of equipment which can perform the basic mission in like fashion. MCERM directs the transfer of substitutions to minimize shortage and distance penalties of other options. MCERM penalizes substitutions (by equipment type) in order to favor the use of required equipment, if available.

D. MODEL DESCRIPTION

MCERM is a mixed-integer, linear program designed to provide a recommended series of equipment transfers (redistribution) within MARFORRES to decrease the equipment shortage experienced by units while minimizing the transfer cost and therefore maximize readiness. In order to accomplish this objective, MCERM minimizes three competing terms: the shortage between what units require and own, the distance-size penalty function for transfers, and the number of substitutions. The model makes use of applied penalties to weight the importance of the competing terms.

E. PENALTY CALCULATION

MCERM relies on minimizing the sum of three penalty functions to model MARFORRES G-4 objectives: regular transfer penalty, substitution transfer penalty, and equipment shortage penalty.

The regular transfer penalty is composed of distance penalty and a cross-MSC penalty. The distance penalty is based on the *pmove* weight. MCERM calculates *pmove* for each set of possible transfers based on the size of equipment being moved and the distance between the two units. The model multiplies the size (cubic feet) to the square root of the distance (miles) to calculate *pmove* for all potential transfers. The applied square root represents the knowledge that as distance continues to increase the differences between shipment costs at such distance become marginally decreasing. Due to the lack of actual cost information, however, this research neither empirically validates this claim nor attempts to adjust an alternative regression model for cost. Therefore, exceptionally far shipments can compete with other transfer options given the effect from the square root of distance. The cross-MSC penalty is based on the *cFactor* weight, which penalizes a transfer between units belonging to different MSCs.

The second penalty function is for substitute transfers. As with regular transfers, a penalty is incurred for the substitute transfer itself (based on distance and for potential crossing of MSCs). In addition, a $psubs_e$ weight penalizes each substitution of equipment *e* selected by MCERM, to reflect the unit commanders' preference to receive the equipment designated for them rather than a substitute. The penalty might encourage a preference for the preferred gear even if at a farther distance. For the purpose of this thesis testing, $psubs_e$ values are based on MEE, MARES, and Non-MARES classification.

The third penalty function is for the inventory gap encountered by units. It uses a penalty term called *pshort*. This cannot simply be a percentage-based penalty, as each unit will own and require varying quantities of equipment. *pshort* is therefore created from the product of four values: $(priority_u^U)^2$, $priority_e^E$, $1/req_{eu}$, and pt_k. The first term, $(priority_u^U)^2$, allows the planner to influence the priority of unit *u* to receive equipment. This term is scaled from one to six, with six being the top priority. The prioritization simplifies the guidance received from the MARFORRES G-3 Operations. The priority is squared to increase the difference and separation between the priority levels while keeping it simple for input. The second term, $priority_e^E$, for equipment type *e*, derives from the equipment prioritization for the Marine Corps. The planner can place priority on different equipment types to increase the overall need to keep units' shortage on these critical items low. For testing purposes, we made these priorities based on mission essential tasks: MEE, MARES, and Non-Mares. The next penalty term, $1/req_{eu}$, creates a scaling mechanism that supports relative importance as measured with respect to the total TA for said equipment type and unit. For example, a unit receiving one equipment item which has a TA of ten will have a greater impact in unit readiness than compared to a unit with TA of 100 and only receiving one item. The last factor segments the shortages in order to apply an approximate a nonlinear penalty (i.e., a penalty with increased rate for larger shortages). A factor, pt_k, where k is the segment index, is used to increase the penalty rate. For the purposes of this thesis, we utilize five segments in testing but a planner can adjust these as needed. For example, a unit may require 20 computers and MCERM applies a five-segment gap so that now each segment represents four computers. Those segments for the shortage penalty are applied so that if the unit is short one to four computers, the same penalty cost is applied per each missing computer. This is true for the other segments as well but the penalty associated with each segment increases. Back to our example, if the unit is short seven computers, then four computers will be charged the first segment penalty (pt_1) and this will be added to the next three computers multiplied by the next segment's higher penalty (pt_2, where $pt_2 > pt_1$). This method ensures that we prefer two units to be short four computers each than for one unit missing eight and the other none. In addition, the shortage penalty has an overall weight, *w*, that allows planners to weight the importance of shortage versus transfer. That is, when *w*=0, the planner disregards any shortage (and no transfers will occur). As *w* increases, a balance between shortage and transfers is realized.

F. FORMULATION

The formulation for MCERM is organized according to standard practices. This section provides the notation and full formulation of the mathematical model.

<u>Indices and sets</u>

e	type of equipment, for $e, e' \in E$
u	UIC for a unit, for $u \in U$
k	set of segments for approximate nonlinear penalty, for $k \in K.$ Note: we use K={1 . . . 5}, (i.e., 5 segments in our test cases).
$F \subset E \times E$	mapping of equipment e to its accepted substitute e', for $f = (e, e') \in F$

c	MSC, for $c \in C = \{$DIV, MLG, MAW, FHG, and H&S$\}$
c_u	MSC for unit *u*

<u>Data [units]</u>

oh_{eu}	quantity on-hand (in-service or disposal status) equipment *e* currently assigned to unit *u*. Externally sourced equipment is viewed as a unit. [units of issue]
$ohinserv_{eu}$	quantity on-hand (in-service only) equipment *e* currently assigned to unit *u*. [units of issue]
req_{eu}	TA requirement quantity of equipment *e* for unit *u*. [units of issue]
$priority_u^U$	priority level of unit *u* to receive equipment; we use levels 1 to 6, with 1 being the lowest. [priority units]
$priority_e^E$	priority level of equipment *e* with which to equip units in order to provide scale to determining shortage penalty; we use levels 5, 10, 15 with 15 being the highest. [priority equipment]
$dist_{uu'}$	distance between unit *u* and unit u'. [miles]
$size_e$	size of equipment *e*. [ft^3/unit]
$crossMSC_{uu'}$	Calculated as: 1 if $c_u \neq c_{u'}$, and 0 otherwise. [unitless]
$cFactor$	penalty factor for transfers between MSCs. [ft^3 $\times$ miles$^{1/2}$ / unit]
$pmove_{euu'}$	penalty for moving equipment *e* from unit *u* to unit u'. Calculated as: $pmove_{euu'} = size_e \sqrt{dist_{uu'}}$. [ft^3 $\times$ miles$^{1/2}$ / unit]
pt_k	factor associated with shortage segment *k* used to determine $pshort_{euk}$. Calculated as: $pt_k = k^{\alpha}$, for $a \geq 1$. (We use a=1). [unitless]
$pshort_{euk}$	penalty for not reaching the TA per equipment *e*, unit *u*, and segment *k*. Calculated as: $pshort_{euk} = (priority_u^U)^2\, priority_e^E \left(1/ req_{eu} \right) pt_k$. [unitless]

$\overline{s}_{euk}$ — length of penalty segment *k*, for equipment *e* and unit *u*. Calculated as

$$\overline{s}_{euk} = req_{eu} \frac{k^2}{\sum_{j \in K} j^2}$$. [units of issue]

w — overall weight of shortage penalty with reference to distance penalty. [ft^3 $\times$ miles$^{1/2}$ / unit]

$psubs_e$ — substitution penalty for equipment *e*. [ft^3 $\times$ miles$^{1/2}$ / unit]

$Imin_e$ — minimum inventory of equipment *e* required for any unit that owns and still requires *e*. [units of issue]

Decision Variables

$X_{euu'}$ — quantity of in-service equipment *e* to assign from unit *u* to unit u'. [units of issue]

S_{euk} — shortage of equipment *e* for unit *u* in penalty segment *k*. [units of issue]

I_{eu} — final inventory of equipment *e* in unit *u*. [units of issue]

$X^F_{ee'uu'}$ — quantity of equipment e substituted by equipment e' to assign from unit u to unit u'. [units of issue]

Formulation

$$\min \sum_{\substack{e,u,u' | req_{eu'}>0,\\ ohinserv_{eu}>0}} (pmove_{euu'} + crossMSC_{uu'} cFactor) X_{euu'}$$
$$+ \sum_{\substack{e,e',u,u' | (e,e') \in F,\\ req_{eu'}>0,\\ ohinserv_{e'u}>0}} (pmove_{e'uu'} + crossMSC_{uu'} cFactor + psubs_e) X^F_{ee'uu'} \tag{1}$$
$$+ \quad w \left(\sum_{e,u | req_{eu}>0} \sum_k pshort_{euk} S_{euk} \right)$$

Subject to:

$$\sum_k S_{euk} \geq req_{eu} - I_{eu} \qquad \forall e,u \,|\, req_{eu} > 0 \tag{2}$$

$$I_{eu} \geq Imin_e \qquad \forall e,u \mid req_{eu} > 0,\ ohinserv_{eu} > 0 \tag{3}$$

$$I_{eu} = oh_{eu} + \sum_{u'|ohinserv_{eu'}>0} X_{eu'u} - \sum_{u'|req_{eu'}>0} X_{euu'} + \sum_{\substack{e'|(e,e')\in F \\ u'|ohinserv_{e'u'}>0}} X^F_{ee'u'u} - \sum_{\substack{e'|(e',e)\in F \\ u'|req_{e'u'}>0}} X^F_{e'euu'} \qquad \forall e,u \mid req_{eu} > 0 \tag{4}$$

$$S_{euk} \leq \overline{s}_{euk} \qquad \forall e,u,k \mid req_{eu} > 0 \tag{5}$$

$$\sum_{u'|req_{eu'}>0} X_{euu'} + \sum_{\substack{e'|(e',e)\in F, \\ u'|req_{e'u'}>0}} X^F_{e'euu'} \leq ohinserv_{eu} \qquad \forall e,u \mid ohinserv_{eu} > 0 \tag{6}$$

$$X_{euu'}, X^F_{ee'uu'} \geq 0 \text{ and integer; } I_{eu} \geq 0;\ S_{euk} \geq 0, \qquad \forall e,e',u,k \tag{7}$$

Objective function (1) contains three terms. The first penalizes transfer distance traveled and crossing MSCs. The second term works similar to the first but adds penalties associated with substitutions. The last term penalizes not meeting TA requirements.

Constraint (2) establishes the shortage variables based on TA and inventory after transfers. Constraint (3) specifies that units should keep a minimum gear of each required type if they already have it. Constraint (4) sets the final inventory as the on-hand equipment adjusted for equipment reassignments. Constraint (5) bounds the shortage in each penalty segment by the length of the segment. Constraint (6) limits the transfers to in-service status equipment. Constraints (7) bound variables and define their domains.

G. OUTPUT

MCERM provides a recommendation for the optimal set of transfers between units which minimize the assigned penalties. We have prepared reports for planners showing MCERM's recommendations as a tiered list first by unit, then by the unit's equipment, then by unit and equipment pairings with the quantity designated to be transferred to recipient unit. This process repeats through all units which are receiving and sending items. The layout of the output recommendations is then repeated again from a sender’s perspective.

H. IMPLEMENTATION

MCERM is computationally implemented in the General Algebraic Modeling System (GAMS) [9] with a CPLEX solver. Test cases have been run on a Lenovo T420 laptop with Intel Core i5 2540M quad-core processor at 2.6 GHz with eight GB of RAM. A typical test case contains 1,500 equipment items and 400 units (a mix of headquarters and subordinate UICs), with average requirements of 120 equipment types per unit. MCERM is separable by item e, if the item does not appear on the substitution list, or if it does, it is separable by groups of related items through substitution. This greatly simplifies the solvability of the problem. In practice, we collect equipment types in groups of up to 40 items even if they are not related by substitution. A typical model for a group of 40 items contains 20,000 variables and 9,000 constraints and solves in between 40 and 240 seconds. The full problem with all groups solved takes approximately 10 to 20 minutes.

IV. ANALYSIS OF RESULTS

This chapter provides the MCERM results from the tested data sets and analyzes the patterns observed.

A. CASE STUDIES

We have used two data sets in order to test MCERM: small-case test and full-case test. Both tests contain full layettes of information with the only difference being the number of units and equipment types considered for optimization.

1. Small-Case Test

The small-case test includes 144 units, three equipment types (A00122B, A77007G, and H77202B), and 187 equipment-to-unit pairings with over 600 individual equipment items. These equipment types are specifically chosen by the author because: (a) their role as substitutes for each other serving as a battery charger; (b) LOGCOM has previously sent these to MARFORRES units; and (c) the relative small quantity to model, with 637 individual equipment items available for optimizing. Further, the number of available equipment ensures that MCERM can reach a possible solution with zero shortage penalty.

2. Full-Case Test

The full-case test includes all equipment and unit ownerships as reported by GCSS-MC on April 22, 2016. This test includes the over 400 units (a mix of headquarters and subordinate UICs), 1,500 equipment types and 42,000 equipment-to-unit pairings with 1.2 million individual equipment items. The overall shortage penalty is calculated as 8,224,410 with no transfers taking place. This testing combines all the elements that MCERM can handle, including transfers already directed for action which are fixed and available LOGCOM equipment.

B. SMALL-CASE TEST RESULTS AND ANALYSIS

1. Results

The small-case test reflects the model's potential for insightful results. The subset equipment and unit pairings equate to a total shortage penalty of 11,106 before transfers (i.e., if the overall shortage weight is set to *w*=0). MCERM conducts 24 test runs varying both *w* and the cross-MSC *cFactor* penalty (Table 2).

Table 2. Small-Case Test Sensitivity Analysis Inputs.

Test Run	1	2	3	4	5	6	7	8	9	10	11	12
w	1	2	3	5	1	2	3	5	1	2	3	5
cFactor	0				1				2			

Test Run	13	14	15	16	17	18	19	20	21	22	23	24
w	1	2	3	5	1	2	3	5	1	2	3	5
cFactor	5				10				50			

In reviewing the results, rather than listing detailed variations of the recommended transfers, we focus on the total penalties and transfer sums as calculated by MCERM's objective function. We divide this into transfer cost (combining the distance, substitution, and MSC crossing penalties) and shortage penalty. For the same group of test runs with the same *cFactor*, we expect to see that as *w* increases (to set values of 1, 2, 3, and 5, respectively), transfer cost increases and the shortage penalty decreases.

The results reflect the recommended solutions for each run and are consolidated in Table 3 to provide a glimpse into MCERM's methodology and solutions.

Table 3. Small-Case Test Results

	Transfer Penalty*	Shortage Penalty**	Quantity equipment transferred	Number of transfers	Number of substitutions
Test Run 1	329	44	118	62	57
Test Run 2	379	2	128	61	67
Test Run 3	384	0	129	66	68
Test Run 4	384	0	129	63	68
Test Run 5	435	57	116	56	55
Test Run 6	507	2	128	64	67
Test Run 7	513	0	129	67	68
Test Run 8	513	0	129	66	68
Test Run 9	853	91	111	55	52
Test Run 10	919	44	118	58	57
Test Run 11	1,009	5	127	61	66
Test Run 12	1,029	0	129	64	68
Test Run 13	1,351	137	107	58	49
Test Run 14	1,449	70	114	54	53
Test Run 15	1,509	44	118	62	57
Test Run 16	1,659	2	128	68	67
Test Run 17	2,300	240	102	51	45
Test Run 18	2,471	110	109	55	51
Test Run 19	2,518	91	111	55	52
Test Run 20	2,689	44	118	57	57
Test Run 21	3,935	1,296	76	38	20
Test Run 22	5,085	378	97	47	40
Test Run 23	5,580	149	106	52	49
Test Run 24	5,796	99	110	58	52

* Includes moving, MSC crossing, and substitute penalties
** Includes shortage penalty, prior to applying the overall shortage weight w

2. Analysis

The analysis of results for the small-case test aids in discerning patterns on the behavior of MCERM that may normally be overlooked with larger problems. In what follows, transfer penalties include the first two terms in Equation (1); that is, moving, crossing MSC, and substitute penalties. Shortage penalty refers to the third term in

Equation (1) but, for comparison purposes, we report that value prior to applying the shortage weight *w*.

We observe the following trends:

- MCERM rebalances equipment in order to minimize transfer costs and shortage penalty as desired. The transfer solution provides a zero shortage penalty with a low shortage weight (*w*=3) adjusted when the cross-MSC penalty *cFactor* is also low (0 or 1). As weight *w* increases with consistent *cFactor*, shortage penalty tends to decrease. Figure 1 illustrates that as weight *w* increases, a generalized decrease occurs in the shortage penalty across the *cFactor* values. These rebalances are complicated by increasing the *cFactor*. As the *cFactor* increases, then the shortage penalty is observed to increase (Figure 2).

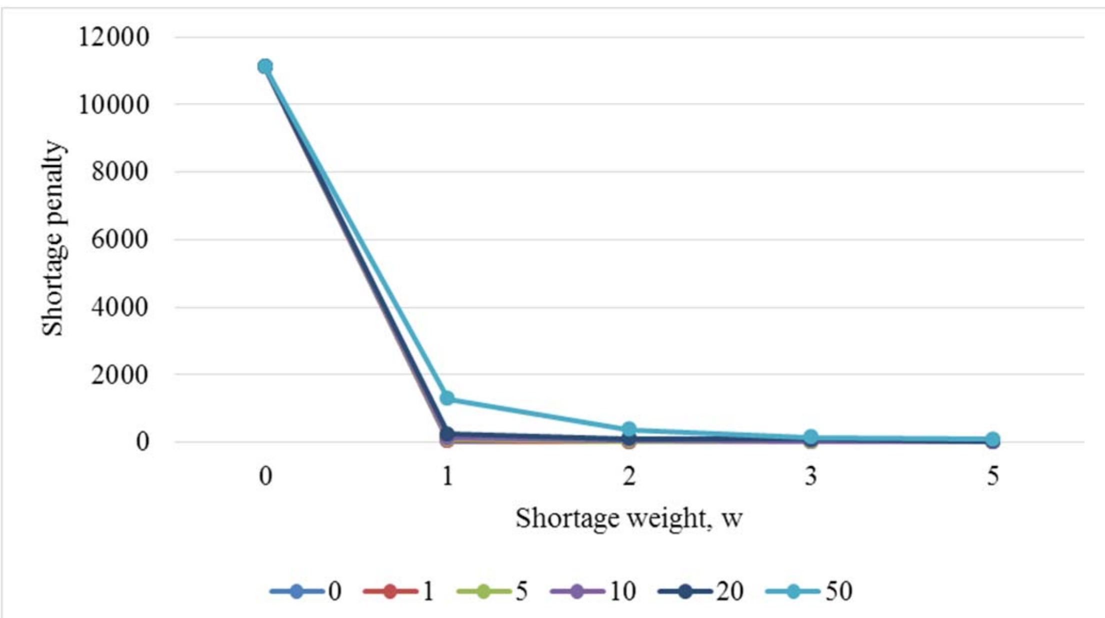


Figure 1. Small-Case: Shortage Penalty as a Function of Weight *w* Increases and *cFactor* Value (colored lines).

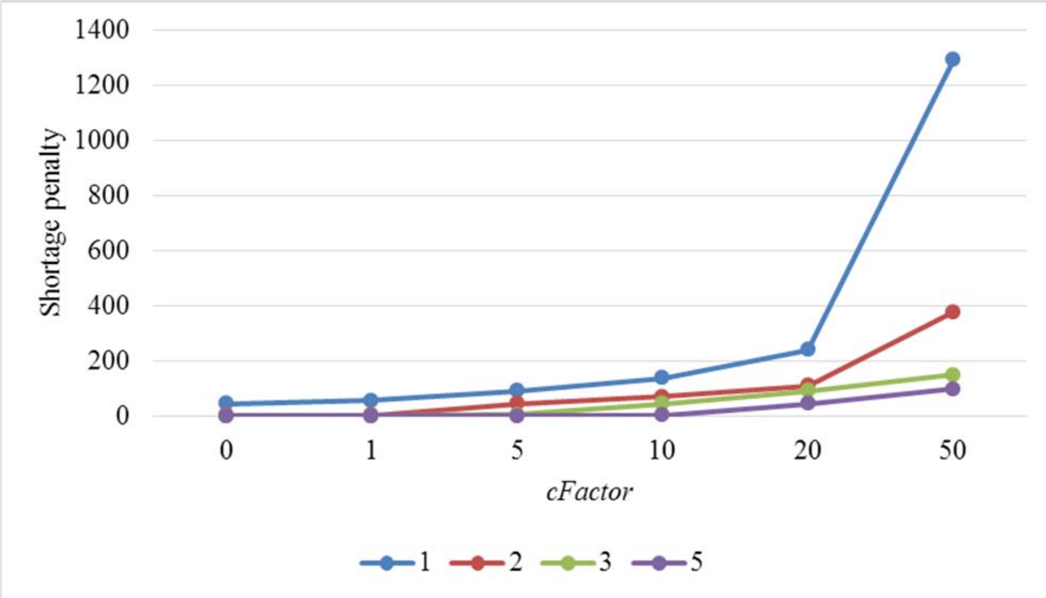


Figure 2. Small-Case: Shortage Penalty as a Function of *cFactor* Increases and Weight *w* Values (colored lines).

- MCERM's rebalance of equipment can further be illustrated by the percentage increases for units' equipment. Figure 3 displays the number of units with associated percentage of their respective required equipment. The "Baseline" graphic shows the shortage before MCERM is utilized. Before optimization, 35 units own less than 60% of the required equipment they need. After only one iteration, with a small shortage weight of *w*=1, the number of units reduces to zero with less than 60% of needed equipment. MCERM redistributes the equipment in a manner that has now raised overall supply readiness for the units while minimizing the transfer cost. The effect of non-linear penalties on shortages is also evident from the balanced redistribution of equipment.

- As expected, as the shortage weight *w* increases, MCERM decreases the shortage penalty while the transfer cost increases (Figure 4).

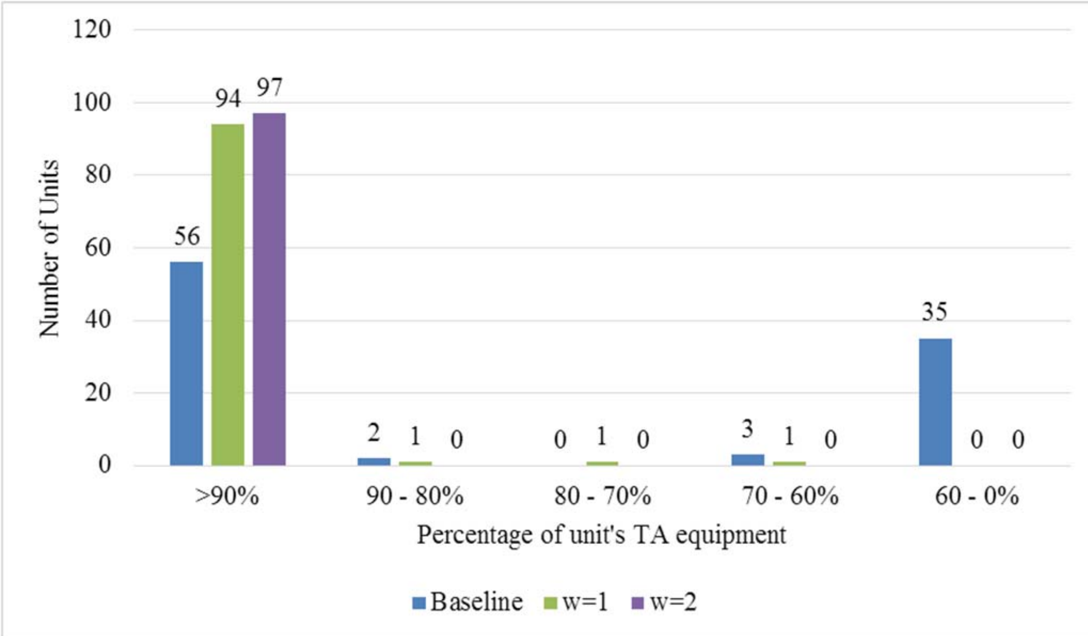


Figure 3. Small-Case: Number of Units by Percentage of TA Equipment and Shortage Weight *w*.

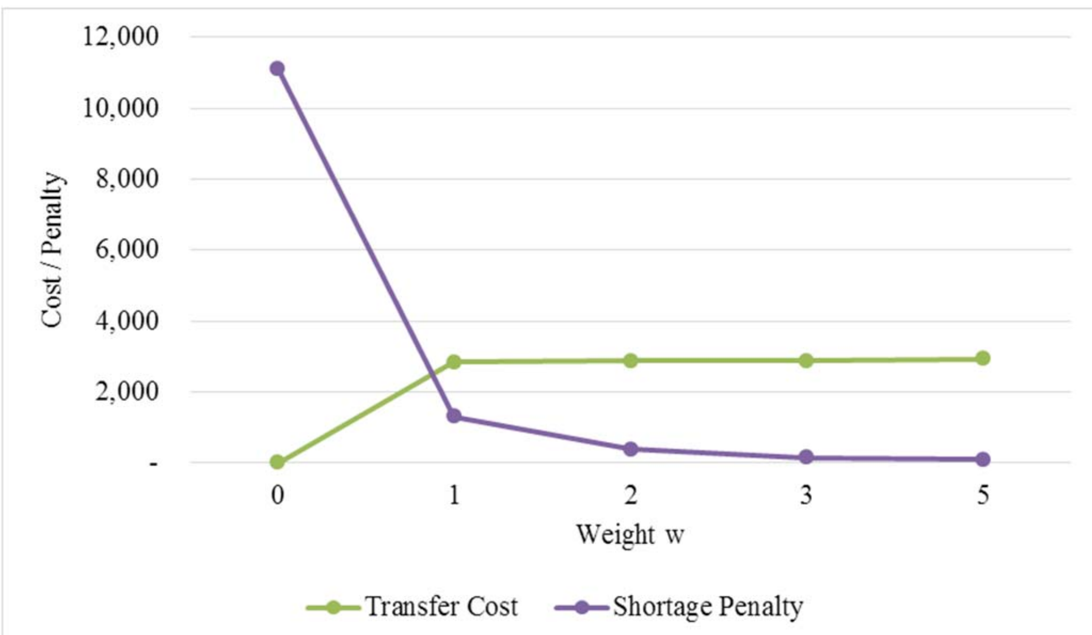


Figure 4. Small-Case: Transfer Cost and Shortage Penalties as a Function of Weight *w*.

- By adjustment of the cross-MSC *cFactor* and shortage weight *w* inputs, MCERM provides a range of different transfer options after the shortage penalty reaches zero. This can be readily affirmed by viewing the changes in the number of transfers adjusting to test runs (see Table 4). Test Runs 4 and 5 both accomplish the same shortage of zero and move the same equipment quantity but the number of transfers and cross-MSC transfers adjust as shortage weight *w* adjusts from 3 to 5. This also occurs with Test Runs 9 10, and 12.

Table 4. Small-case: Test Runs that Reach Shortage Penalty of Zero and Provide Different Transfer Recommendations.

Test Run	*w*	*cFactor*	Shortage Penalty**	Quantity equipment transferred	Number of transfers	Number of substitutions	Number of cross MSC
3	3	0	0	129	66	68	38
4	5	0	0	129	63	68	45
7	3	1	0	129	67	68	45
8	5	1	0	129	66	68	46
12	5	5	0	129	64	68	42

** Includes shortage penalty, prior to applying the overall shortage weight *w*

C. FULL-CASE TEST

1. Results

The full-case test results provide insights into behavior and a review of the entire equipment set owned by MARFORRES and how they might be able to utilize MCERM to improve their readiness. A “movers list” has been used with each test run in order to replicate scheduled LOGCOM shipments and currently available equipment for MARFORRES for the month of April. Further, unlike in the small-case test, the full-case test represents the present predicament of “not enough equipment to supply everyone.” Therefore, some shortage penalties for equipment types cannot be reduced.

The test runs are completed by adjusting the shortage weight *w* and the cross-MSC *cFactor* as in the small-case. However, we run tests that increase *w* by approximately an order of magnitude (1, 2, 5, 10, 10^2, 10^3, 10^4, and 10^5, respectively) and set *cFactor* to 0, 10, 50, 100, and 1000 (see Tables 5–9).

Table 5. Full-Case: *cFactor* =0.

Weight	Transfer Penalty*	Shortage Penalty**	Number of Transfers	Quantity Transferred	Number of Substitutions	Number of cross MSC
1	495,659	4,795,195	11,395	222,700	9,467	5,404
2	911,262	4,505,924	12,992	280,057	14,233	6,490
5	1,904,005	4,189,985	15,146	367,876	22,970	8,073
10	2,934,618	4,043,199	16,345	415,674	26,800	8,749
100	13,249,969	3,748,358	18,297	481,290	30,194	10,042
1000	38,030,679	3,653,405	19,044	495,598	30,717	10,492
10000	47,861,976	3,648,023	19,273	498,193	30,700	10,619
100000	50,816,446	3,647,886	19,424	500,548	30,696	10,730

* Includes moving, MSC crossing, and substitute penalties
** Includes shortage penalty, prior to applying the overall shortage weight *w*

Table 6. Full-Case: *cFactor* =10.

Weight	Transfer Penalty*	Shortage Penalty**	Number of Transfers	Quantity Transferred	Number of Substitutions	Number of cross MSC
1	888,162	5,334,561	8,636	60,232	5,207	4,211
2	1,392,902	4,976,385	10,239	87,188	8,314	5,094
5	3,016,257	4,486,264	12,693	175,608	15,738	6,584
10	5,362,759	4,152,141	14,906	293,242	22,886	8,066
100	17,839,756	3,749,868	18,132	466,868	29,879	9,932
1000	42,925,408	3,653,455	19,041	493,795	30,701	10,493
10000	52,838,103	3,648,024	19,260	497,945	30,684	10,634
100000	55,819,214	3,647,886	19,420	500,328	30,680	10,740

* Includes moving, MSC crossing, and substitute penalties
** Includes shortage penalty, prior to applying the overall shortage weight *w*

Table 7. Full-Case: *cFactor* =50.

Weight	Transfer Penalty*	Shortage Penalty**	Number of Transfers	Quantity Transferred	Number of Substitutions	Number of cross MSC
1	727,876	6,689,280	4,375	12,583	906	2,275
2	2,087,340	5,727,650	7,320	35,304	3,198	3,773
5	4,264,355	5,020,947	10,048	69,643	7,309	5,247
10	6,906,972	4,656,607	11,680	106,651	12,244	6,156
100	33,066,319	3,771,740	17,485	405,806	28,569	9,601
1000	61,962,973	3,653,956	18,934	483,767	30,517	10,398
10000	72,729,530	3,648,025	19,239	497,507	30,680	10,604
100000	75,821,642	3,647,886	19,411	500,205	30,676	10,745

* Includes moving, MSC crossing, and substitute penalties
** Includes shortage penalty, prior to applying the overall shortage weight *w*

Table 8. Full-Case: *cFactor* = 100.

Weight	Transfer Penalty*	Shortage Penalty**	Number of Transfers	Quantity Transferred	Number of Substitutions	Number of cross MSC
1	406,498	6,689,280	4,375	12,583	273	1,319
2	1,530,526	5,727,650	7,320	35,304	1,046	2,532
5	5,125,306	5,020,947	10,048	69,643	4,581	4,485
10	8,535,465	4,656,607	11,680	106,651	8,074	5,526
100	46,698,239	3,771,740	17,485	405,806	26,261	9,293
1000	85,301,971	3,653,956	18,934	483,767	30,324	10,391
10000	97,551,401	3,648,025	19,239	497,507	30,677	10,619
100000	100,826,973	3,647,886	19,411	500,205	30,674	10,735

* Includes moving, MSC crossing, and substitute penalties
** Includes shortage penalty, prior to applying the overall shortage weight *w*

Table 9. Full-Case: *cFactor* =1000.

Weight	Transfer Penalty*	Shortage Penalty**	Number of Transfers	Quantity Transferred	Number of Substitutions	Number of cross MSC
1	16,777	8,206,124	43	222	3	30
2	462,670	7,954,607	492	1,426	45	254
5	2,020,306	7,483,639	1,662	3,623	104	926
10	4,809,713	7,092,452	2,961	4,722	328	1,652
100	84,932,897	4,657,631	11,388	75,165	8,596	6,119
1000	387,529,017	3,721,438	17,461	351,054	26,769	9,702
10000	526,182,556	3,648,964	19,055	478,698	30,323	10,443
100000	548,236,420	3,647,906	19,341	498,307	30,666	10,715

* Includes moving, MSC crossing, and substitute penalties
** Includes shortage penalty, prior to applying the overall shortage weight *w*

2. Analysis

The analysis of the full-case test reviews only large trends and behaviors through total penalties and transfers. We observe the following trends:

- The shortage penalty and transfer penalty continue their relationship that as one increases the other will decrease illustrating the tradeoff involved in redistribution of equipment (Figure 5). This shows the efficient frontier (also known as Pareto curve) of the problem for the two given objectives (shortage versus transfer penalty). Points on this curve are guaranteed that no solution can be found that improves either objective without worsening the other.

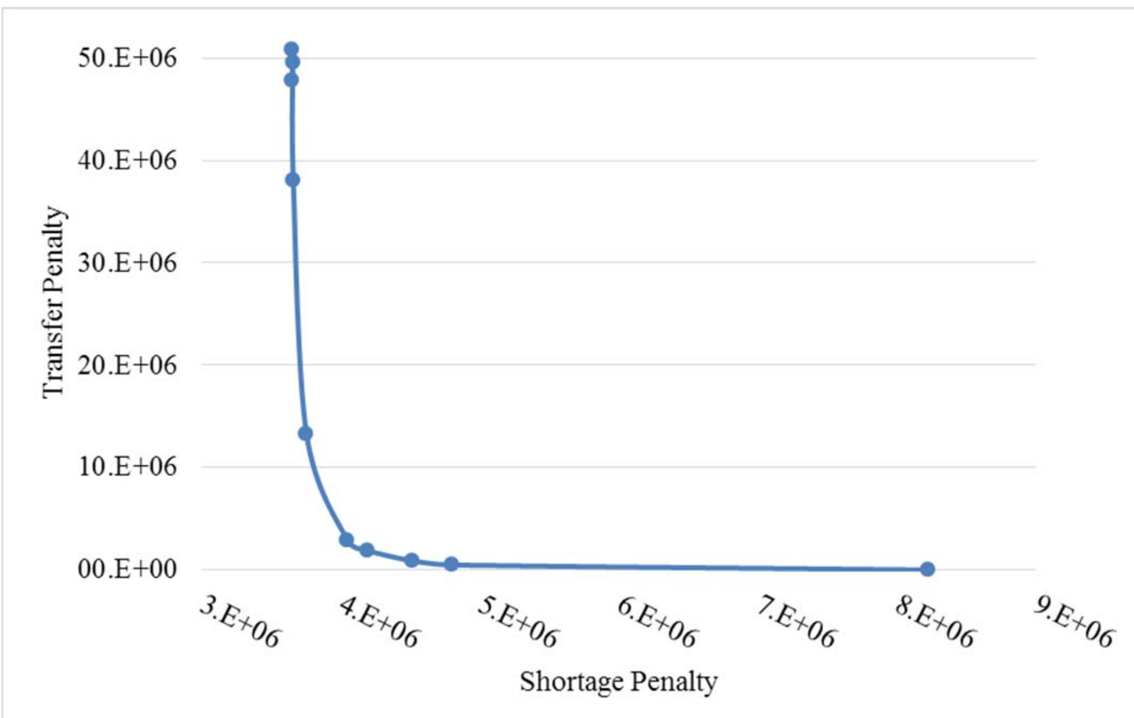
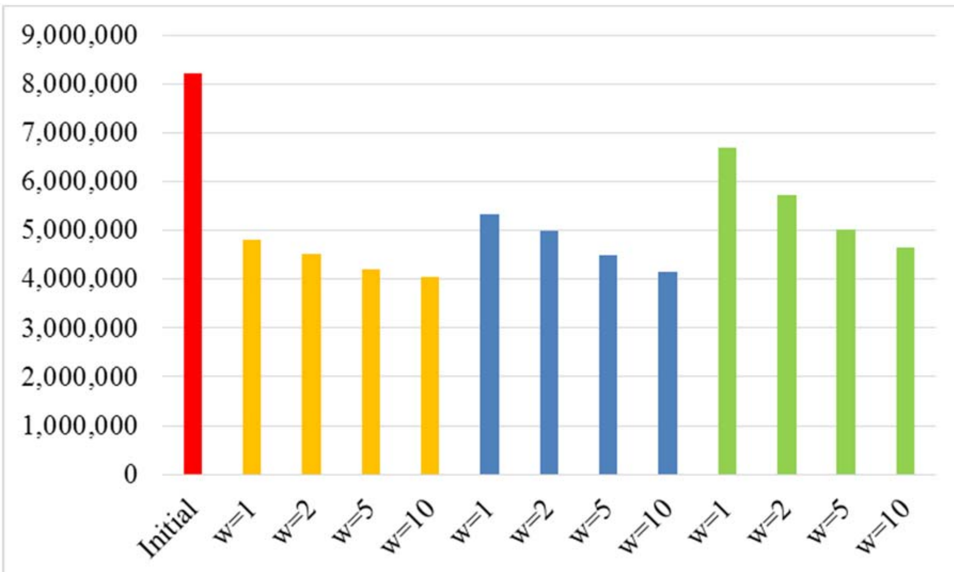


Figure 5. Full-Case: Transfer Cost as a function of Shortage Cost (efficient frontier).

- MCERM nearly halves the shortage penalty with shortage weight, *w*, set as 1 and 2. Weight *w*=10 seems to half the entire shortage penalty when the cross-MSC *cFactor* is kept minimal. MCERM demonstrates that significant gains in supply readiness can be reached with a small transfer penalty in the optimized redistribution. Figure 6 illustrates this point with the high red penalty bar demonstrating the initial shortage penalty encountered and the successive bars grouped and colored by varying *cFactors*. However, this trend is counter manned by increasing the *cFactor*. The green bars on the Figure 6 demonstrate that the shortage penalty remains inflated through the lower applied weights until *w*=10.



The red bar represents initial shortage penalty (w=0); cFactor values of 0, 10 and 50 are depicted in yellow, blue, and green, respectively.

Figure 6. Full-Case: Shortage Penalty as a Function of Shortage Weight *w* and Cross-MSC *cFactor*.

- Increasing cross-MSC *cFactor* value results in higher shortage penalties, which can be better illustrated in Figure 7 (where each line represents a different *cFactor*). MCERM successfully limits the number of cross MSC transfers by increasing the *cFactor*.

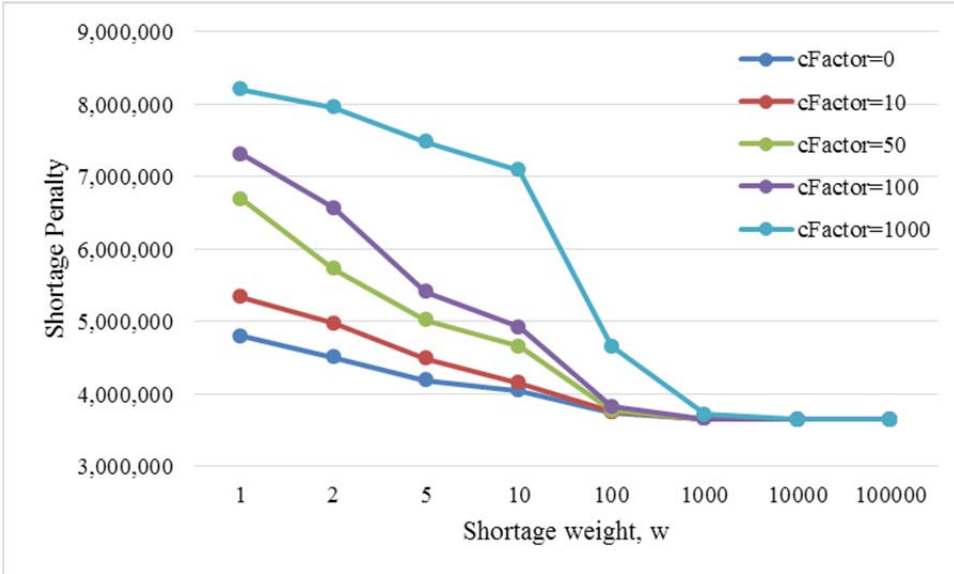


Figure 7. Full-Case: Shortage Penalty as a Function of Shortage Weight *w* and Cross-MSC *cFactor.*

- MCERM's solutions reach an eventual plateau in most of the result fields compared to the relatively large weight applied to the test runs. The shortage penalty appears to decrease no farther than 3,640,000 (see Figure 7) regardless of the weight *w* or *cFactor* combinations. This penalty floor is a limit that cannot be reduced further unless new equipment is added. A similar behavior is observed with the number of equipment transferred and number of transfers taking place (see Figures 8 and 9). This plateauing reflects the boundary of resources available within which MCERM can optimize the equipment redistribution.

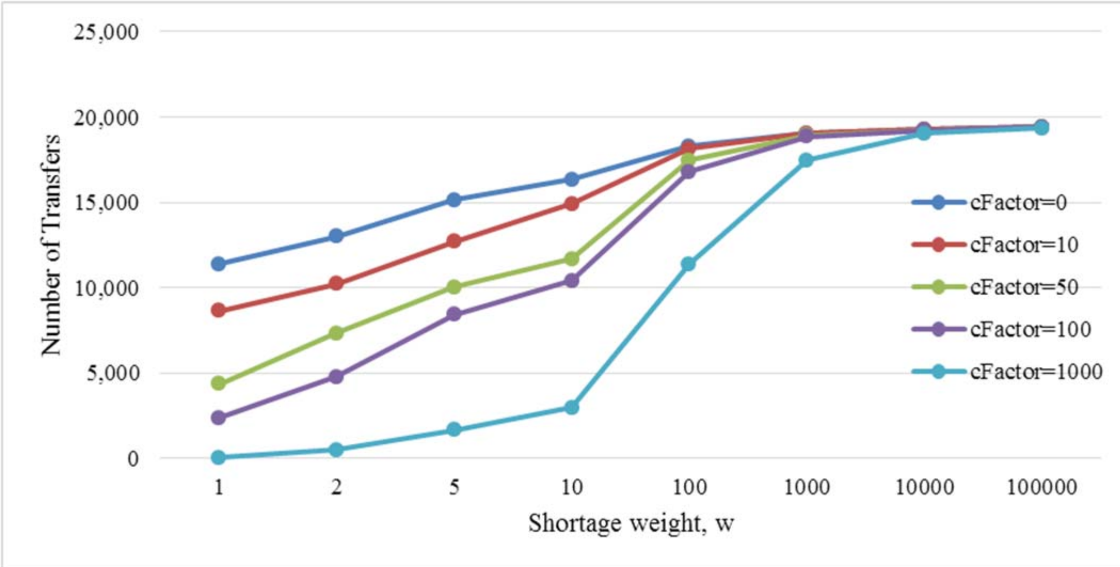


Figure 8. Full-Case: Number of Transfers as a Function of Shortage Weight *w* and Cross-MSC *cFactor*.

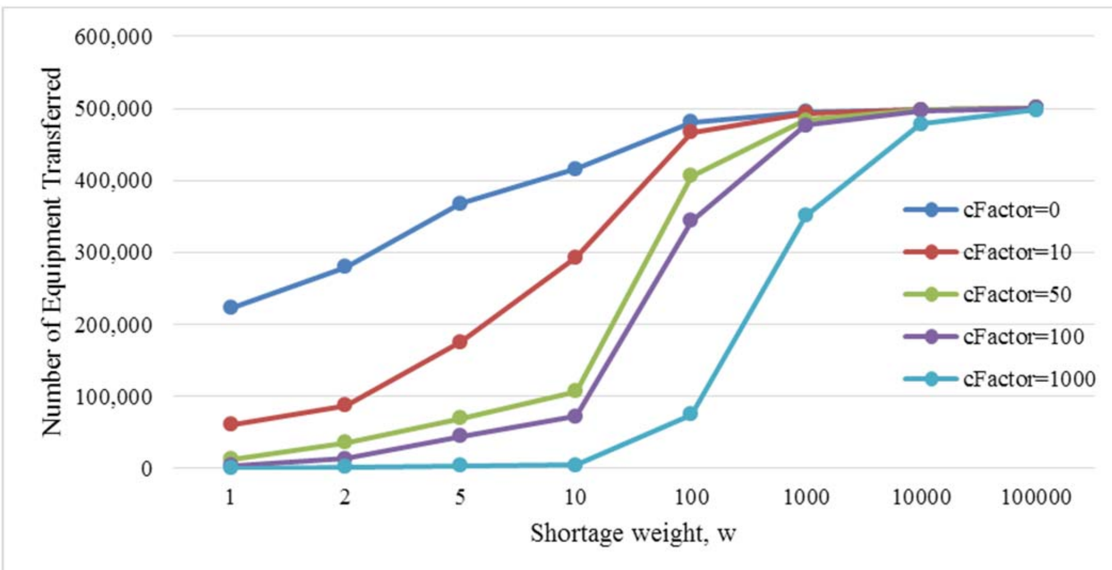


Figure 9. Full-Case: Equipment Quantity Transferred as a Function of Shortage Weight *w* and Cross-MSC *cFactor*.

- MCERM produces a significant increase in the substitution penalty between shortage weights *w* from 10 to 100, as illustrated in Figure 10. This observation suggests that at this tipping point, substitutions will be more heavily employed in decreasing the shortage penalty. The number of substitutions increases at a much lower rate with additional shortage weight.

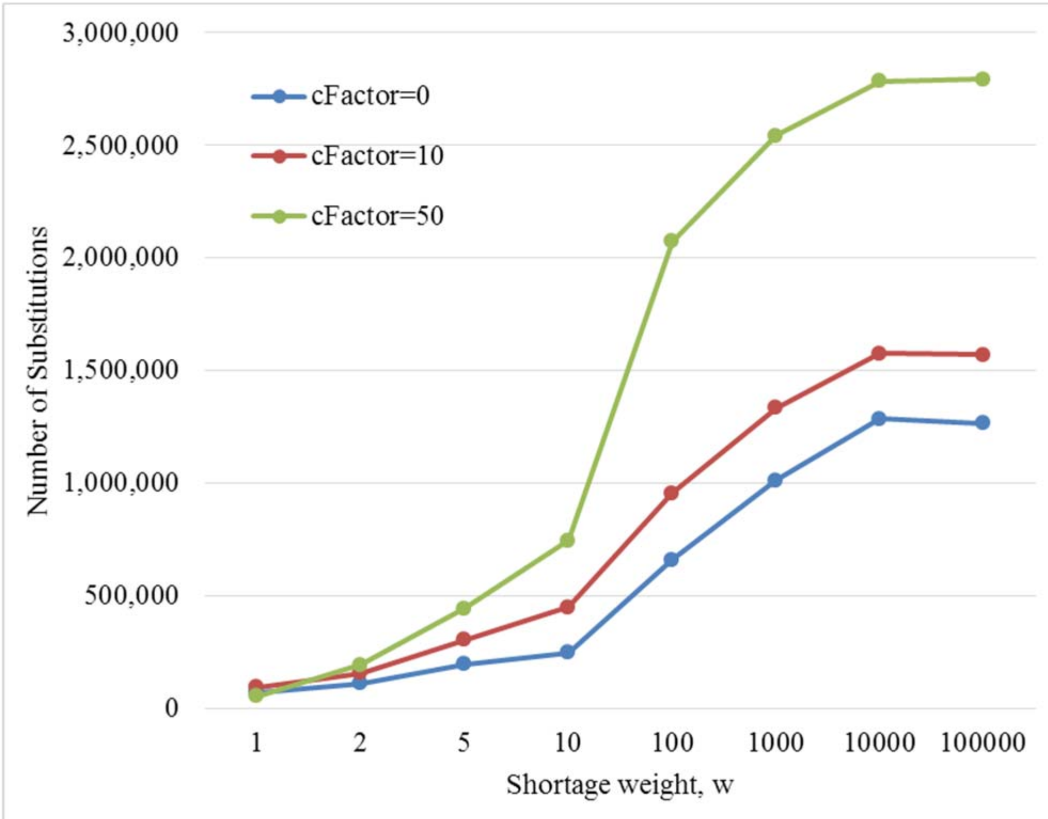


Figure 10. Full-case: Substitution Penalty by shortage Weight *w* and Cross-MSC *cFactor.*

- MCERM successfully rebalances the entirety of the MARFORRES equipment set to increase the number of units at over 80% ownership of their TA equipment. The initial baseline from data received shows about 20 units operating at above 80% of their equipment requirement. MCERM provides a solution to increase this number to 150 units and halve the number of units operating below 60% of their TA equipment (see Figure 11).

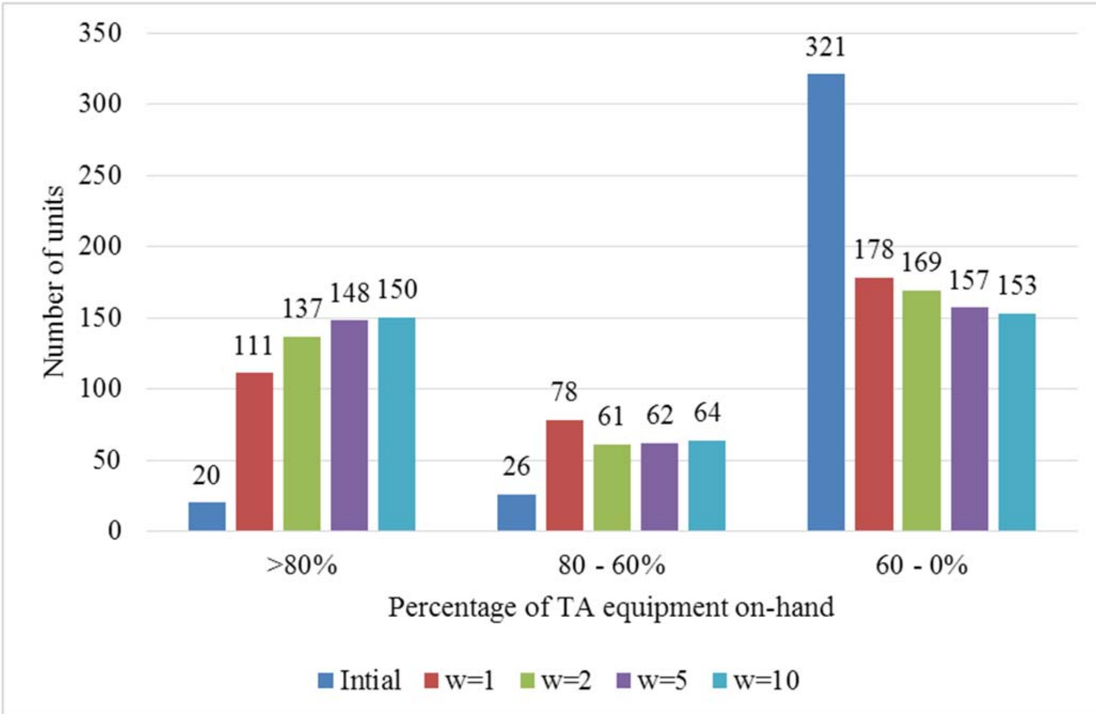


Figure 11. Full-Case: Number of Units with given Percentages of TA Equipment as a Function of Shortage Weight *w* and Cross-MSC *cFactor=2*.

V. SUMMARY AND FUTURE WORK

This chapter reviews the conclusions drawn from the testing analysis and offers recommendations for continuation of enhancements and future work for MCERM.

A. CONCLUSIONS

Lieutenant General Richard Mills, former Commanding General of MARFORRES, remarks in his vision and strategy document [10], that "Deficiencies in individual or unit equipment have a direct impact on Force readiness." He directly links MARFORRES operational readiness as a whole to the ability for units to possess the needed equipment with which to train and operate. MCERM provides the high-value, formal optimization analysis with which planners' can improve the decision making process of equipment transfers and support the General's directive to improve readiness.

1. Value of MCERM

The most important value of MCERM is its ability to balance unit readiness and transfer cost across the force. A single planner is significantly limited in this capacity due to the myriad of alternatives for equipment and substitute-equipment transfers, and the several competing goals. MCERM uses formal optimization to review the complete MARFORRES equipment inventory redistribution problem and provide a series of recommended transfers. This guidance can be of great help to human analysts in order to improve their decision making.

Through smarter transfers, the shortage experienced overall by the forces in equipment can be dramatically reduced. MCERM allows planners to weight the importance of different competing objectives, such as transfer penalty versus inventory shortage, in order to generate solutions on the efficient frontier of the problem. As observed in Figure 5, such analysis quickly identifies solutions that reduce overall equipment shortages by half across the force at a relatively low transfer penalty. Further decreasing the inventory shortages beyond this point incurs much larger transfer penalties. With transfer penalty as a rough surrogate for the cost to ship items between

RTCs, MCERM provides the ability to save money while increasing readiness as demonstrated in Figure 11 and related analysis.

MCERM eliminates the tiresome task of a planner cross checking distances and substitutions by referencing provided data files. A planner's task to rebalance the force's equipment quickly becomes enormously tedious with referencing lists of distances between units, equipment size, unit importance, and substitutions.

In addition, substitutions are well-utilized in MCERM solutions developed in this research, but not used very often by MARFORRES in practice, in part due to the complexity of such analysis. Thus, MCERM is capable of exploring (and providing the planners with) new solutions to improve readiness.

2. Recommendations for Use

MCERM provides the ability to optimize redistribution of all equipment across all units, or to scale the size of redistribution to what a planner wants reviewed. The staff working group currently divides types of equipment amongst themselves (i.e., one person manages the vehicles, another person handles the communications equipment). Now these planners can use MCERM only on their relevant equipment segment. Scaling by types of equipment sets is not the only method to reduce the review but MCERM can be used to redistribute or issue one specific equipment type. This is beneficial for analyzing single-equipment concerns.

MARFORRES can also utilize MCERM in standing up Special-Purpose Marine Air-Ground Task Forces (SP-MAGTF) or in the distribution of new equipment. The creation of a new SP-MAGTF requires sourcing equipment from units across the Marine Corps to support the creation of a new unit developed for a specific mission with a rapidly approaching deployment. It is usually difficult to plan which units should send equipment to support a new unit. MCERM may alleviate the work by providing a way for the planner to add a new unit with new requirements, and recommending the best options to support the sourcing.

B. FUTURE WORK

The work developed in this thesis has produced the MCERM as a prototype for use in equipment redistribution and is ripe for continued study and further enhancements, as described in the following items:

- A multi-period MCERM can provide a solution that spreads across periods with changing priorities. Similar to Persons' MPORAM, a multi-period MCERM can provide a new dimension in planning equipment transfers by anticipating long-term effects of short-term redistributions. These time-phased transfers can be potentially more manageable and have the desired buildup effect over time of equipment needed for MARFORRES units. Further, using a multi-period model allows unit prioritization to change by period and better model MARFORRES current practices.

- MCERM creates a surrogate penalty to model shipping costs of equipment but this can be improved to more accurately model actual cost (e.g., per mile and by type of equipment). The transfer penalty used in MCERM enables the minimization of travel by miles and respective equipment size. However, this figure cannot be connected to an actual cost in shipments. Development of an enhanced transfer penalty provides planners the ability to relate savings in transfer solutions and, for example, keep within a designed budget.

- Another potential development is to use MCERM with LOGCOM and active duty units to increase operational readiness in S-ratings. The use of MCERM in MARFORRES provides a method for redistribution among units which is also a current practice in the active duty units. Often units are required to deploy small platoons or teams to participate in exercises requiring the sourcing of various equipment types. This process is usually handled at the local MSC level. However, if the LOGCOM used this to review the entire force, different optimal options may be discovered. LOGCOM's advantage would be the ability to review the entire Marine

Corps equipment-unit pairings and find the choice that costs the least amount while contributing to operational readiness.

- MCERM solutions assume that all equipment is operational and not currently undergoing maintenance. A future development can have MCERM review all current maintenance reports and select equipment that is in a maintenance ready status. This enhancement becomes a timesaving method as planners can avoid selecting units to transfer equipment with non-operational equipment. As the transfer message goes out to units and returns with a negative response, days or weeks may have past requiring the transfer to become expedited and a suboptimal choice must now be made.
- MCERM can also improve transfer cost savings by providing solutions in grouped quantities for special-care items (previously described as bonded shipments). The bundling of equipment means that there would be less transfers and consequently less shipment-related costs for the same quantity of shipped equipment.
- Lastly, MCERM can further enhance shipment transfer recommendations by layering MARFORRES command unit structure and relationships. The UICs modeled by MCERM are a mix of subordinate and headquarters units all of which have command relationships designating which unit is responsible for another. The layering of these relationships can improve transfers by accounting for higher headquarters ownership of a subordinate’s equipment. Therefore, there should be a penalty to discourage MCERM from shipping equipment between units which are not under the same headquarters.

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